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Thermal performance analysis of vacuum variable-temperature blackbody system

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HIGHLIGHTS

- The design and structure of a vacuum variable-temperature blackbody system were described.
- The steady-state thermal analysis of a simplified 3-D blackbody model was performed using finite element analysis.
- The performance of the blackbody was evaluated by the signal transfer function and noise equivalent temperature difference.

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ABSTRACT

In this paper, the design and structure of a vacuum variable-temperature blackbody system were described, and the steady-state thermal analysis of a 3-D blackbody model was presented. Also, the thermal performance of the blackbody was evaluated using an infrared camera system. The blackbody system was constructed to operate under vacuum conditions (2.67×10^{-2} Pa) to reduce its temperature uncertainty, which can be caused by vapor condensation at low temperatures usually below 273.15 K. A heat sink and heat shield including a cold shield were embedded around the radiator to maintain the heat balance of the blackbody. A simplified 3-D model of the blackbody including a radiator, heat sink, heat shield, cold shield, and heat source was thermophysically evaluated by performing finite elements analysis using the extended Stefan–Boltzmann's rule, and the infrared radiating performance of the developed system was analyzed using an infrared camera system. On the basis of the results of measurements and simulations, we expect that the suggested blackbody system can serve as a highly stable reference source for the calibration and measurement of infrared optical systems within operational temperature ranges.

1. Introduction

Recently, the demand for radiation thermometers, infrared sensors, and infrared cameras has increased for commercial and research purposes. Together with this trend, applications of the blackbody system have also increased for analyzing measurement precision of infrared sensors and calibration [1–4]. Palchetti et al. [5] designed and characterized a small and cost-effective reference blackbody sources for radiometric calibration of Fourier transform spectrometers in the mid- and far-infrared region. They also described the optimization of the absorbing black-coating material and the study of two types of cavity geometry. A blackbody system can be commonly defined as a precision radiant heat-generating device whose emissivity is close to 1.0; it is used for calibrating devices that measure wideband infrared radiant heat. Most existing blackbody systems use liquids such as oil or water as a refrigerant. When these systems are used in an environment with sub zero temperatures or in which the temperature difference is large compared to the experimental environment, it is difficult to precisely control or generate the temperature and emissivity owing to problems arising from the condensation of the air in a blackbody system. This, in turn, leads to operation instability and measurement imprecision problems [6–8]. Fowler [9] designed and constructed a high-temperature oil-bath-based blackbody, and reported the blackbody source operates in the 293–473 K range with blackbody temperature combined standard uncertainties ranging from 7.2 to 30.9 mK. In addition, existing commercial blackbody systems are relatively large, which causes inconvenience during operation. Therefore, various researches for the different purposed blackbody systems have been conducted in

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order to solve the water vapor condensation problem at sub-zero temperatures [10]. Ogarev et al. [11] presented the details of low-temperature precision blackbodies that were developed at the All-Russian Research Institute for Optical and Physical Measurements (VNIIOFI). These blackbodies have been used in the world's leading space research institutions such as SDL (USA), DLR (Germany), Keldysh Space Center (Russia), RNIIKP/RISDE (Russia), NEC Toshiba Space Systems (Japan) as the spectral radiance and irradiance calibration devices.

Herein, the design of a vacuum variable-temperature blackbody system that is smaller and easy-to-move as compared to the existing blackbody systems was presented. Furthermore, thermal analysis of the simplified 3-D blackbody model was conducted using finite element analysis (FEA). The operational performance of the blackbody system was also evaluated by analyzing the signal transfer function (SiTF) and noise equivalent temperature difference (NETD).

2. Design and construction

Fig. 1 shows the cross section and 3-D layout of the vacuum variable-temperature blackbody system, which consists of ten major devices: (A) radiator made of oxygen-free copper, (B) heating device (thermoelectric element), (C) platinum resistance type thermometer, (D) aperture window, (E) heat shield, (F) cold shield, (G) heat sink, (H) thermoelectric control connector, (I) vacuum port, and (J) refrigerant port. A disk-type radiator (diameter: 80 mm, thickness: 10 mm) was manufactured using oxygen-free high thermal conductivity copper (OFHC) whose thermal conductivity was 391 W/mK [12]. The OFHC material was cut and machined using an ultra-precision five-axis diamond turning machine (Freeform 700A, Precitech Inc., USA), and the surface roughness and form accuracy were measured using a laser interferometer (WYKO 6000, Veeco, USA) as 46.75 nm and 348.45 nm, respectively [13]. The surface of the radiator was precisely coated with 0.03 mm thickness using black paint (Aeroglaze Z306, LORD corp., USA) to improve its thermal emissivity as the manufacturer has recommended.

The operating temperatures of the blackbody system range from 268 to 333 K, which was mainly determined by the heating element capacity. All components of the blackbody were placed under vacuum conditions to minimize the temperature uncertainty of the radiator caused by vapor condensation, which may occur from temperature difference between inside the blackbody and environments. The blackbody system is primarily heated by a Bi–Te thermoelectric element (RD-253, TETECHNOLOGY Inc., USA) which controlled by a power controller (VBBS-M570, IRWAVE Inc., Korea). Temperature resolution and the time required for 5 °C change of the power controller are 1 mK and 70 s, respectively. As shown in Fig. 1(A) and (C), a thin film type resistance temperature detector (S245PD12, Minco Inc., USA) was embedded in the radiator for the temperature control of primary heating of blackbody. Tolerance of the resistance temperature detector and temperature measuring range are ±0.06% and from −70 °C to 400 °C, respectively. Measured temperature from a resistance temperature detector was used for the temperature feedback control using the power controller which is connected with a thermoelectric element. Each of heating and cooling was individually accomplished by its Peltier effects. The Peltier effect can be defined as the presence of heat at an electrified junction of two different metals, and we can control the temperature of the blackbody by changing the direction of the electrical current in a Peltier device. Only for the secondary heating above 283 K, a heat shield wrapped with copper wire was activated and controlled by the same power controller used in the primary heating. A set temperature of the secondary heating was synchronized with that of primary heating. In addition, a same resistance temperature detector used in the temperature measurement of radiator was also embedded in the heat shield for the temperature feedback control of secondary heating of blackbody. A Peltier device used in the heating process was also primarily applied to cool the blackbody down. Just like the control of heating process, a thin film type resistance temperature detector (S245PD12, Minco Inc., USA) which embedded in the radiator was used for the temperature feedback control of primary cooling of blackbody. For the secondary cooling of blackbody, a liquid refrigerant which imported through a refrigerant port was applied. The liquid refrigerant used in this blackbody was pure water. In addition, the cold shield which shown in Fig. 1(F) was designed to help the cooling process additionally. Structurally the cold shield directly contacts with the heat sink which can be cooled by a liquid refrigerant, and the temperature of liquid refrigerant was maintained as 283 K by temperature controller (RC-320, LCDV Inc., Korea) during cooling process. The heat shield was placed around the radiator, and both the radiator and heat shield were

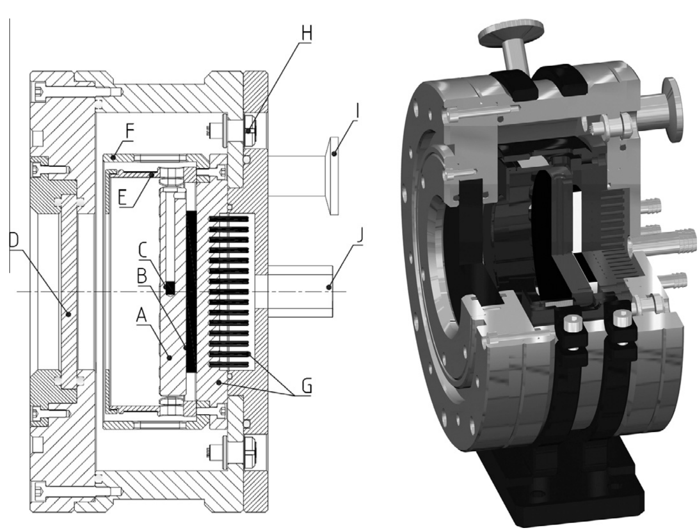

Fig. 1. Cross section and 3-D layout of vacuum variable-temperature blackbody; (A) radiator made of oxygen-free copper, (B) heating device (thermoelectric element), (C) platinum resistance type thermometer, (D) aperture window, (E) heat shield, (F) cold shield, (G) heat sink, (H) thermoelectric control connector, (I) vacuum port, and (J) refrigerant port.